International Conference on Textile Composites and Inflatable Structures
STRUCTURAL MEMBRANES 2011
E. Oñate, B. Kröplin and K.-U.Bletzinger (Eds)

NUMERICAL INVESTIGATION OF THE STRUCTURAL BEHAVIOUR OF A DEPLOYABLE TENSAIRITY BEAM

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Key words: Tensairity, deployable structures, inflatable structures

Abstract. This paper investigates numerically the load bearing behaviour of a deployable Tensairity beam. More precise, it studies the influence of the cables that connect the upper and lower strut of the deployable Tensairity beam on its load bearing behaviour. Finite element analysis shows that these cables are pretensioned when the airbeam is inflated. When both diagonal and vertical cables are present, only the vertical cables become tensioned. These tensioned cables are able to take compressive forces, by the same amount as their initial pretension. This has as result that these cables avoid the hinges to deflect under compression. Or in other words, the pretensioned cables 'block' the hinges. Once the external load has reached the value whereby the value of the pretension becomes zero in at least one cable, the hinge is not blocked or supported anymore by this cable. The hinge will experience larger displacements and the stiffness of the deployable Tensairity beam decreases.

1 INTRODUCTION

Inflatable structures have been used by engineers and architects for several decades. These structures offer lightweight solutions and provide several unique features, such as collapsibility, translucency and a minimal transport and storage volume. In spite of these exceptional properties, one of the major drawbacks of inflatable structures is their limited load bearing capacity. This is overcome by combining the inflatable structure with cables and struts, which results in the structural principle called Tensairity.

1.1 Tensairity structures

Tensairity is a synergetic combination of struts, cables and an inflated membrane (by low pressurized air), as illustrated in figure 1. The tension and compression elements are physically separated by the air inflated beam, which – when inflated – pretensions the tension element and stabilizes the compression element against buckling.

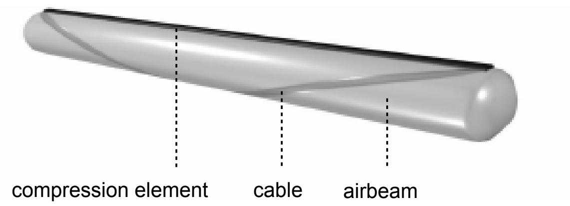

Figure 1: The basic cylindrical Tensairity beam [1].

A Tensairity structure has most of the properties of a simple air-inflated beam, but can bear several times more load [1]. This makes Tensairity structures very suitable for temporary and mobile applications, where lightweight solutions that can be compacted to a small volume are a requirement. However, the standard Tensairity structure cannot be compacted without being disassembled. By replacing the standard compression and tension element with a mechanism, a deployable Tensairity structure is achieved that needs - besides changing the internal pressure of the airbeam - no additional handlings to compact or erect the structure.

1.2 Foldable truss system

A promising concept for a deployable Tensairity structure has been developed by Luchsinger [2], inspired by the foldable trusses of Santiago Calatrava. Calatrava developed in 1981 in his PhD-dissertation 'Zur Faltbarkeit von Fachwerken' ('On the folding of trusses') novel deployable structures by introducing hinges in trusses and by investigating their kinematics [3]. One of his deployable structures is a conventional truss where the horizontal tension and compression bars of each triangle are divided in two and reconnected with an intermediate hinge (figure 2). This way, the truss becomes a mechanism. To stabilize the system in deployed configuration, Calatrava applied vertical bars and a locking mechanism at the intermediate hinges.

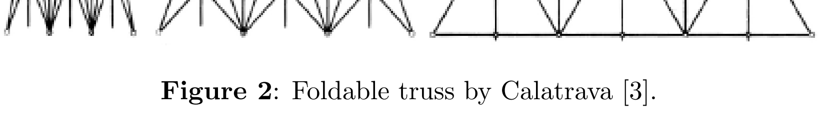

Figure 2: Foldable truss by Calatrava [3].

Luchsinger adjusted the system for applying it in a Tensairity structure by replacing the vertical bars with (pre-tensioned) cables, as illustrated in figure 3 [2]. The diagonals can be included or excluded and materialized as struts or cables. The linear compression and tension elements, resp. on the upper and lower side, are in the deployable Tensairity structure continuously attached with the hull, and this way, the truss is stable when the air beam is fully inflated. The structure can be folded and unfolded without disassembling, as illustrated in figure 4.

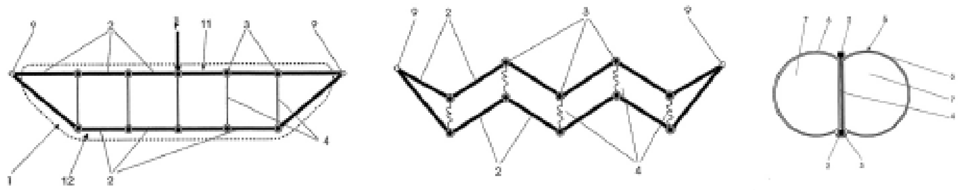

Figure 3: Foldable truss for Tensairity beam by Luchsinger et al. [2].

Figure 4: The deployment sequence of the foldable truss [2].

2 PHYSICAL AND NUMERICAL MODEL

A physical model (with its simplifications and approximations) is applied in this section for a basic understanding of the effect of interactions between load, pressure, membrane, compression element and cables. Conclusions derived from this simplified model are verified by means of a numerical model.

As mentioned, the investigated deployable Tensairity beam is constituted of an air-beam, an upper and lower strut and cables connecting the hinges of upper and lower strut. Figure 5 illustrates a longitudinal and sectional view of the structure that will be investigated in this paper.

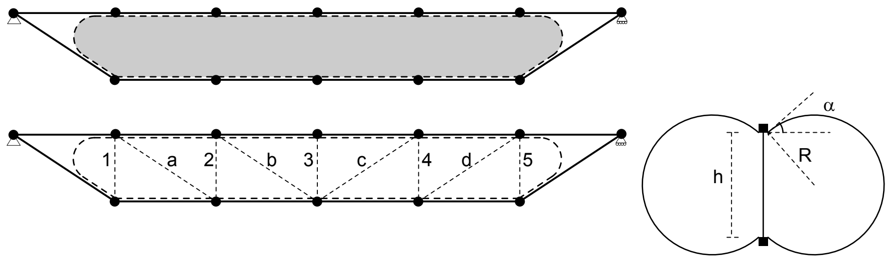

Figure 5: A longitudinal and sectional view of the deployable Tensairity beam.

2.1 Inflation

When *inflating* the airbeam, the overpressure pushes the upper and lower struts outwards and the hull tends to become a circle. This action will be counterbalanced by the cables that connect the compression and tension element. As a result, the cables become tensioned and experience thus a tensile force. The value of this force can easily be calculated.

For inflated beams, the radial membrane tension n_{radial} $[\frac{N}{m}]$ is the product of the radius of the hull and the internal overpressure: $n_{radial} = p \times R$. As a result, the cable force F in one cable equals

$$F = 2 \times p \times R \times l \times sin(\alpha) \tag{1}$$

with α being the angle between the membrane (tangential) and the horizontal (indicated in figure 5) and l the distance between two adjacent cables. This normal force F $[N]$ can also be called the pretension in the cable due to inflation (F_{pre}).

The deployable Tensairity beam with vertical and diagonal cables connecting upper and lower strut (as shown in figure 5) is investigated by means of finite element calculations in ANSYS. The finite element model, illustrated in figure 6, is inflated with an internal overpressure of 100 mbar ($p = 10\ \frac{kN}{m^2}$). The beam is isostatically supported and has a length of 2 m. The distance between adjacent vertical cables (length l) measures 0.333 m. The airbeam has a radius R of 0.127 m, a height h of 0.25 m between upper and lower strut and an angle α between the hull and the horizontal of 10°.

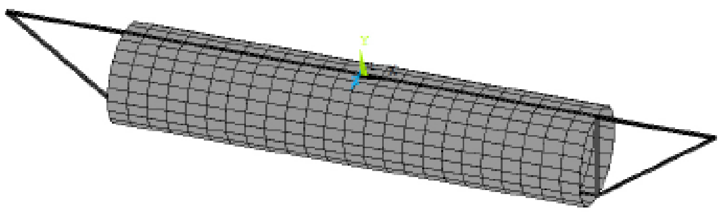

Figure 6: The deployable Tensairity beam is also investigated numerically. The airbeam is only modeled until the first and last cable for reasons of convergence.

From the figure can be seen that no end caps are modeled: the membrane is not fully closed at the ends and only modeled until the first cable. Otherwise, the hull interfered with the struts and convergence was an issue. It is the scope of further studies to ameliorate this finite element model. This approximation has as result that the cables closest to the ends (cable 1 and 5) experience half of the calculated and expected pretension ($\frac{1}{2}F_{pre}$). The cable pretension derived from the numerical calculations is 149 N for the middle cables and 74,5 N for cables 1 and 5. All forces introduced by inflation are taken by the vertical cables. The diagonals are not pretensioned under inflation because of their angulated position.

The pretension in the vertical cables is also calculated with equation 1. With using the same parameters as in the finite element model, one obtains the value of 147 N, which is a good approximation of the numerical value.

2.2 Loading

The cable pretension is decreased by *loading* the deployable Tensairity beam (downwards). When the amount of external load taken by one cable is equal to the pretension in this cable (F_{pre}), it becomes slack. This means that the cable has from that point on zero stiffness and cannot support any additional compressive loading. As a consequence, the cable does not contribute anymore to the structural behaviour and one can expect the stiffness of the Tensairity beam to change at the value whereby the cables become slack.

The deployable Tensairity beam from figure 5 is loaded with a point load in each upper hinge. If F_{ext} is the total amount applied load, then in each hinge a load of $\frac{1}{5}F_{ext}$ is applied. From standard trusses, one knows that the first verticals (cable 1 and 5) experience a compression force of $\frac{1}{2}F_{ext}$. This means that these cables become slack when $F_{pre} = \frac{1}{2}F_{ext}$ or $F_{ext} = 2F_{pre}$. Since the cables 1 and 5 are tensioned with a normal force of 74,5 N, the maximal load this deployable Tensairity beam can bear before changing stiffness is thus 149 N.

This is also investigated by means of finite element calculations on the model presented in figure 6. The displacement of all upper hinges is noted and the average value in relation to the applied load is illustrated in figure 7. From the curve can clearly be seen that the stiffness changes at a total load of approximately 150 N, which corresponds with the analytical derived value. The graph on the right in figure 7 shows the same curves, but with a scaled x-axis to illustrate the stiffness of the airbeam and deployable Tensairity beam after 150 N. Figure 8, plotting the tension in the cables throughout loading, shows that cables 1 and 5 indeed reach zero tension at this value. The graph also shows that the diagonal cables are tensioned under loading, as is also the case for a truss with the same configuration of diagonals. This holds true until cable 1 and 5 become slack. From that point on, the tension force in the diagonals decreases.

The deployable Tensairity beam has also been investigated numerically under various pressures. Figure 9 shows the load-displacement graph of the case under 50, 100 and 200 mbar. As long as all cables are pretensioned, all curves have the same stiffness.

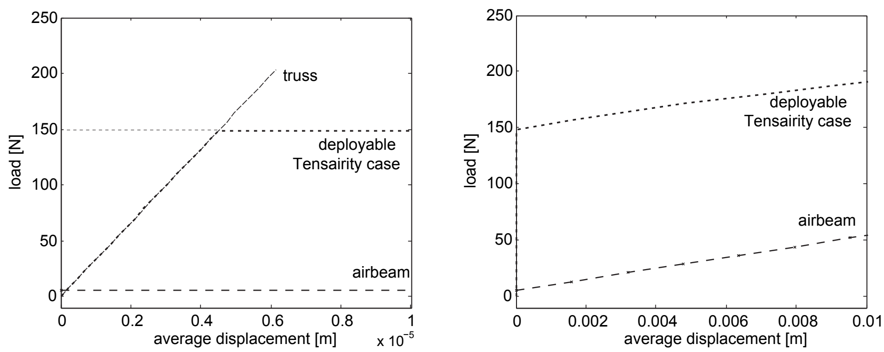

Figure 7: Left: Average displacement of the upper strut in relation to the applied load. (pressure is 100 mbar, five point loads in upper hinges). (Numerical results). Right: same curves, but the x-axis is scaled to show the stiffness of the airbeam and deployable Tensairity beam.

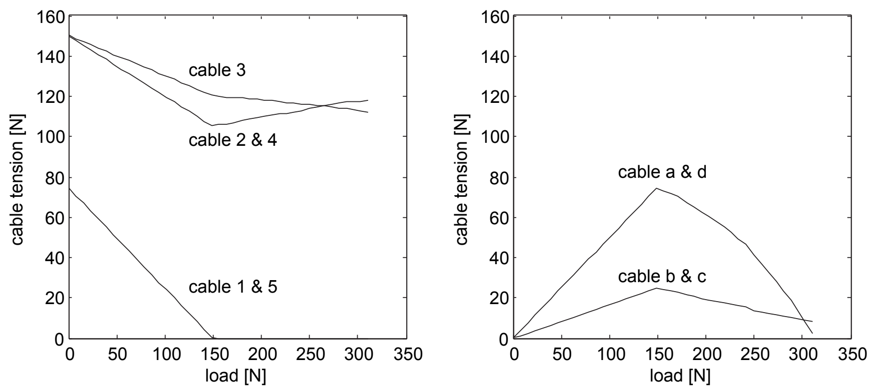

Figure 8: The tension in the cables in relation to the applied load. (Numerical results).

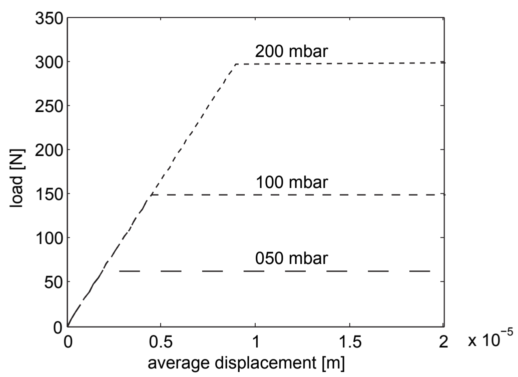

Figure 9: The load-displacement graph of the deployable Tensairity beam under 50, 100 and 200 mbar (loaded with five point loads in the hinges) (Numerical results).

Because the pretension in the cable is dependent of the internal pressure (equation 1), the case with the lowest internal pressure experiences as first a slack cable and thus another stiffness.

When all cables are pretensioned and thus able to take compressive forces, the deployable Tensairity beam has the same stiffness as a truss (with the same configuration of diagonals and with the same sections). This can be seen in figure 7. Once a cable does not contribute anymore to the structural behaviour, the bar structure becomes a 'mechanism'. This is illustrated in figure 10. However, the deployable Tensairity beam does not collapse immediately since it is still supported by the airbeam. This is why the stiffness of the beam is similar to the stiffness of an airbeam after the first cables are slack (figure 7).

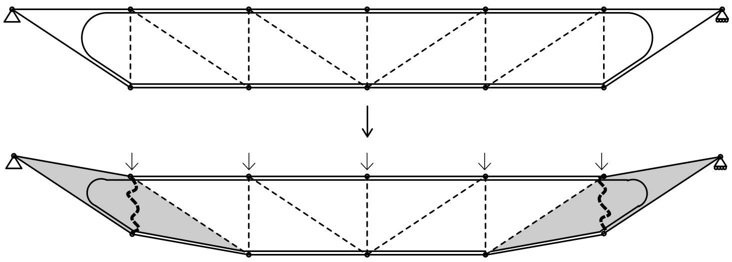

Figure 10: Once a cable does not contribute anymore to the structural behaviour, the bar structure becomes a 'mechanism'.

3 CONCLUSIONS

The influence of cables on the structural behaviour of the deployable Tensairity beam is investigated in this paper. Finite element simulations confirm the physical model and show a relation between the structure's load-displacement behaviour and the contribution of pretensioned cables.

The cables connecting upper and lower strut that are pretensioned at inflation are able to take compressive forces, by the same amount as their initial pretension. This has as result that these cables avoid the hinges to deflect under compression. Or in other words, the pretensioned cables 'block' the hinges and the structure's stiffness is similar to the stiffness of a truss. Once the external load has reached the value whereby the value of the pretension becomes zero in at least one cable, the hinge is not blocked or supported anymore by this cable. The hinge will experience larger displacements and the stiffness of the deployable Tensairity beam decreases.

Further research will focus on the validation of these numerical findings by means of experimental investigations on a two meter prototype. Also, a more detailed numerical model will be developed and implemented. In addition, several cable configurations will be investigated.

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